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Natural hazards in Australia: extreme bushfire

Jason J. Sharples[1] **· Geoffrey J. Cary**[2] **·**
Paul Fox-Hughes[3] **· Scott Mooney**[4] **· Jason P. Evans**[5] **·**
Michael-Shawn Fletcher[6] **· Mike Fromm**[7] **·**
Pauline F. Grierson[8] **· Rick McRae**[9] **· Patrick Baker**[10]

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Abstract Bushfires are one of the most frequent natural hazards experienced in Australia. Fires play an important role in shaping the landscape and its ecological dynamics, but may also have devastating effects that cause human injuries and fatalities, as well as broad-scale environmental damage. While there has been considerable effort to quantify changes in the occurrence of bushfire in Australia, a comprehensive assessment of the most extreme bushfire cases, which exact the greatest economic and environmental impacts, is lacking. In this paper we reflect upon recently developed understanding of bushfire dynamics to consider (i)

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✉ Jason J. Sharples
j.sharples@adfa.edu.au

[1] School of Physical, Environmental and Mathematical Sciences, University of New South Wales, Canberra, ACT, Australia

[2] Fenner School of Environment and Society, The Australian National University, Acton, ACT, Australia

[3] Bureau of Meteorology, Hobart, TAS, Australia

[4] School of Biological Earth and Environmental Sciences, University of New South Wales, Sydney, NSW, Australia

[5] Centre for Excellence for Climate System Science and Climate Change Research Centre, University of New South Wales, Sydney, NSW, Australia

[6] School of Geography, University of Melbourne, Parkville, VIC, Australia

[7] US Naval Research Laboratory, Washington, USA

[8] Ecosystems Research Group, School of Plant Biology, University of Western Australia, Crawley, WA, Australia

[9] Australian Capital Territory Emergency Services Agency, Canberra, Australia

[10] School of Ecosystem and Forest Sciences, University of Melbourne, Richmond, VIC, Australia

historical changes in the occurrence of extreme bushfires, and (ii) the potential for increasing frequency in the future under climate change projections. The science of extreme bushfires is still a developing area, thus our conclusions about emerging patterns in their occurrence should be considered tentative. Nonetheless, historical information on noteworthy bushfire events suggests an increased occurrence in recent decades. Based on our best current understanding of how extreme bushfires develop, there is strong potential for them to increase in frequency in the future. As such there is a pressing need for a greater understanding of these powerful and often destructive phenomena.

1 Introduction

For millennia fire has been a driving force shaping terrestrial ecosystems across Australia — simultaneously charring or scorching significant portions of vegetated landscapes and initiating regeneration (Bradstock and Cohn 2002). Fire remains a conspicuous feature of the contemporary Australian environment and a significant feature of the national psyche. Bushfires result in real costs to the Australian public in terms of loss of life (Chapman 1999), infrastructure and livestock, as well as impacting on agricultural and forest productivity. The total annual cost of fire in Australia has been estimated at around $8.5 billion or 1.15 % of the country's GDP (Ashe et al. 2009). The economic impact of the 2009 Black Saturday bushfires alone was estimated at $4.4 billion (Teague et al. 2010). Other forms of loss include cultural assets (e.g. loss of historic sites), scientific facilities (e.g. astronomical observatories), extensive environmental damage (e.g. Worthy and Wasson 2004), and the often severe and long-lasting psychological stress suffered by firefighters and members of the public (Thomson 2013).

In the past decade or so, major bushfires at the ex-urban margins of Sydney, Canberra, and Melbourne have burnt more than a million hectares of forests and woodlands and resulted in the loss of more than 200 lives and 4000 homes (e.g. Teague et al. 2010). Moreover, loss of property and life are increasing in other major urban expansion areas in Australia, prompting questions about the changing nature of fire events in such densely populated areas. Concern in Australia is centred on the occurrence or perception of a shift to a significantly more hazardous fire regime, characterised by increasing fire frequency and intensity associated with dynamic fire propagation, and the development of catastrophic 'fire storms'. This concern is shared in relation to a variety of landscapes around the globe, where such high-impact fires are referred to as 'mega-fires' (Attiwill and Binkley 2013). The increased incidence of mega-fires around the world has been linked to varying extents to late twentieth Century climate change, most particularly increased drought and higher temperatures (e.g. Liu et al. 2010), in addition to changes in land management policy (Williams 2013). However, we note that a precise definition of an extreme bushfire remains elusive.

Here we define an extreme bushfire (ExB hereafter) to be a fire that exhibits deep or widespread flaming in an atmospheric environment conducive to the development of violent pyroconvection, which manifests as towering pyrocumulus (pyroCu) or pyrocumulonimbus (pyroCb) storms (Fig. 1; Fromm et al. 2010). This involves a coupling of the fire with the atmosphere well above the mixing height, which modifies or maintains the fire's propagation. While large, intense bushfires can occur without deep convective column development (these have been termed "wind-driven" fires), ExBs are associated with a higher level of energy, chaos, and nonlinearity. This is due to the enhanced (fire-induced) interaction between the

Fig. 1 Example of an extreme bushfire with pyroCb – the Grampians Fire, Victoria, 21 February 2014. Photograph taken by Randall Bacon

boundary layer and the free troposphere, which may introduce factors that act to maintain or enhance widespread flaming. These include mid-level moist instability, wind shear, latent heating inside the convective cloud, increased ignition likelihood through lightning and more intense spotting. Due to their size and unpredictability, ExB events consistently result in considerable damage.

The dual landscape management objectives of environmental conservation and minimization of fire-associated risks to life and property have prompted volatile public debate about what fire regimes might be appropriate in different landscapes of contemporary Australia. The management of fire, particularly at the urban-bush interface, is still an area of active research interest (e.g. Gibbons et al. 2012). However, effectively forecasting the future risk presented by very large fires, and ExBs in particular, requires disentangling the influences of fire management efforts from the effects of climatic variability, and any inter-relationships or feedbacks between these factors (Flannigan et al. 2009; Bradstock 2010; Bowman et al. 2014).

Studies into the potential impacts of climate change on the risk of bushfire have taken several approaches, but most tend to focus on broad-scale indices of fire danger or their components (Williams et al. 2001; Clarke et al. 2011). In particular, the majority of Australian studies have focused on changes in the McArthur Forest Fire Danger Index (FFDI), which incorporates measures of surface temperature, relative humidity, wind speed and drought (Noble et al. 1980). However, recent research into the incidence of ExBs in southeast Australia has indicated that the FFDI only serves as a broad-scale prerequisite for ExB occurrence, and that the confluence of other factors is critical in their development (McRae and Sharples 2014). These factors include extended drought and low fuel moisture content, which are captured in FFDI to some extent, along with high atmospheric instability, a conducive topographic setting, and discrete weather events that occur in connection with certain synoptic patterns (Hasson et al. 2009; Sharples et al. 2010). Dry lightning also plays a role in ExBs, both as a source of ignition as well as a result of ExB development (Dowdy and Mills 2009). Comparatively little attention has been devoted to documenting historical changes in these myriad factors and how they might be affected under likely climate projections, particularly in the context of bushfire.

The main objective of this paper is to explore the factors contributing to the occurrence of ExBs in Australia. We review the state of knowledge pertaining to both historical and projected future changes in ExB. In doing so, we focus on the forested areas of southern Australia, and southeastern Australia in particular, as this is where the most significant human impacts have been experienced over the last few decades (Gill et al. 2013). This is not meant to imply that other parts of Australia are not affected by ExBs. Indeed, the forested areas of South Australia and Western Australia have also recorded a recent spate of ExBs (e.g., the Yarloop fires of early 2016 which destroyed 121 homes and cost two lives). While we consider that the key concepts developed from our analysis have relevance to these regions, they are not explicitly addressed here.

ExBs are only one of the natural hazards being covered in this special issue, and there are important connections and parallels to be drawn between bushfire and other hazards, particularly drought and heatwaves. It must be emphasised that research into ExB development is still a nascent area of scientific inquiry – a number of unresolved questions designed to stimulate research into climatic change and ExB incidence are presented in the concluding remarks.

2 Drivers of extreme bushfires in forested landscapes

Fire danger in forested landscapes of southeastern Australia is assessed using McArthur's FFDI, which is defined as (Noble et al. 1980):

$$\mathrm{FFDI} = 2\exp(-0.45 + 0.987\ln D + 0.0338T - 0.0345H + 0.0234U),$$

where D is a relative measure of fuel availability called the drought factor (0–10), T is air temperature (°C), H is relative humidity (%) and U is average wind speed at 10 m (km h^{-1}). Basically, fire danger increases under hotter, drier and windier conditions, and under more severe drought.

Observations of ExBs have shown that consideration of FFDI in isolation does not provide good guidance on the behaviour of these events. For example, Chatto (1999) describes a fire that developed into a large plume-driven event under only a 'High' fire danger rating, while other studies have noted the tendency for FFDI-based models to underpredict the rate of advance of ExBs (e.g. Cruz et al. 2012).

It is important to note that the effect of drought on fire danger (FFDI) is only accounted for by the drought factor up to its maximum value of 10, as envisaged by McArthur (1967); any further deepening of drought conditions cannot be accounted for. The FFDI was designed primarily with reference to small experimental fires burning in fine dead fuels under milder weather conditions. However, in ExBs a greater proportion of living and dead biomass can contribute to energy release, including larger fuel elements such as branches and logs. The various (live and dead) elements of the biomass respond to extended drought on differing time scales, and the effects of these responses on fire behaviour are not necessarily well accounted for in the FFDI. Flammability of larger dead fuel is mostly absent from Australian bushfire research, and while there has been some consideration of the flammability of live fuels (e.g. Caccamo et al. 2012), these factors are yet to be formally incorporated into fire danger indices.

The implication is that indices like the FFDI may not capture the dynamic drying of larger (live and dead) fuel elements, and consequently may not account for their effects on fire propagation and energy release. Similarly, the effects of heatwaves on bushfire fuels are not comprehensively accounted for by the FFDI; while fine fuels are able to recover from the effects of heatwaves within days (Sullivan and Matthews 2013), larger fuel elements will respond to changes in ambient environmental conditions over longer time scales.

ExBs can be considered as being composed of one or more blow-up fire events, which are defined as instances when a fire exhibits a rapid increase in rate of spread and intensity, and penetration of the plume well above the mixed layer (McRae and Sharples 2011). McRae and Sharples (2014) introduced a process model for predicting blow-up events, which incorporates FFDI as a precondition only. The model stipulates that blow-up fire events are only predicted to occur if a number of additional factors combine simultaneously over the same part of the landscape. These include: strong winds and very low fuel moisture content, wind direction change, rugged terrain, and the degree to which the atmosphere is conducive to deep convective plume development, which is assessed in Australia using the continuous Haines (c-Haines) index (Mills and McCaw 2010).

Although the scientific state of knowledge regarding the prime triggers for violent pyroconvection and pyroCb occurrence is still far from complete, there is general agreement that in addition to an atmospheric environment conducive to deep convection, a large (spatial) integral of instantaneous energy release (IIER) is required. That is, at the point of pyroCb onset the flaming zone is unusually large and flame-front intensity is simultaneously great. McRae et al. (2015) refer to such a development as ‘deep flaming’ and demonstrate a spatiotemporal link between deep flaming events and ExB occurrence.

Deep flaming can be produced by a number of mechanisms, operating variously on flat, undulating or rugged terrain with sufficiently heavy fuels. These include:

- Very strong winds – so the headfire advances more rapidly than the back of the flaming zone;
- Change in wind direction – so the long flank of a fire is transformed into a fast running head fire;
- Eruptive fire behaviour – where steep slopes can cause a fire to accelerate rapidly;
- Vorticity-driven lateral spread – where strong winds and steep terrain interact to rapidly drive a fire laterally, accompanied by downwind spotting (Simpson et al. 2013); and
- Mass spotting – where multiple spot fires coalesce to form large areas of flame.

These factors each contribute to the IIER associated with fires and thus contribute to perturbing the atmosphere above the fire. If this perturbation takes place in an atmospheric environment characterised by large values of the c-Haines index, then ExB development can be expected.

In a number of instances, fires have produced significant pyroCbs within hours of ignition. For example, in southeastern Australia, the Big Desert (17 December 2002) and Kilmore East (7 February 2009) fires ignited only several hours before pyroCb development. Such instances provide opportunities to better quantify the fuel, terrain and atmospheric drivers of ExB, and improve our ability to assess their risk in different landscapes under a changing climate.

3 Palaeo-historical perspectives on extreme bushfire in Australia

To determine if ExBs are occurring outside the bounds of historical variability, an appropriate historical context is required. Unfortunately, data on fire occurrence in Australia span only a short period of time and high-quality instrumental records (e.g. satellite coverage) are even shorter. This shortage of information confounds attempts to establish historical benchmarks for fire activity in a location such as Australia, where climatic variability is high and infrequent extreme climatic events may be more important than climate averages.

'Palaeo-environmental' information arising from tree-ring records and sediments from lakes and swamps, can be used to reconstruct fire histories to a certain degree. Tree ring information has been successfully used to develop a spatially explicit analysis of fire return intervals in southwestern Australia and to assess the role of climate anomalies in driving wildfire occurrence and the spatial extent and patterns of very large fires in the region (O'Donnell et al. 2011a, 2011b). However, these approaches are more challenging to apply in the eucalypt forests of southeastern Australia owing to a paucity of tree species that provide clear or annual rings (Heinrich and Allen 2013). More problematic is the fact that in ExB events a greater proportion of trees can be killed, which can compromise the quality of any potential dendrochronological information. An extended climate history for southeast Australia, such as the recent 500 year ANZDA drought atlas (Palmer et al. 2015), may ultimately provide some insights into the temporal and spatial occurrence of extreme fires in recent centuries. Reconstructing specific information about other drivers of ExB development such as atmospheric instability and the passage of strong frontal systems will inevitably be more problematic, and so the contribution of such factors through time are likely to remain obscured.

Quantitative analysis of sedimentary charcoal records allows reconstruction of fire activity at deeper timescales than dendrochronogical records but they are of coarser temporal resolution and often lack spatial constraint. Combining statistical and multi-proxy sedimentary analysis can provide greater insight into what charcoal records indicate in terms of fire frequency and severity (Fletcher et al. 2014, 2015). However, given the bias for charcoal sediments to reflect higher-impact fires (Higuera et al. 2011) within a smaller spatial (i.e. catchment) scale, they may not distinguish large, expansive conflagrations from smaller fires. The development of well-dated spatial networks of sedimentary charcoal records, while not immune to the above limitations, provides some degree of constraint over the trends in fire occurrence through space and time. One such example from southwest Tasmania revealed (1) a tight coupling between decadal- to centennial-scale climate variability and bushfire occurrence and (2) a sharp spike in fire activity in response to anthropogenic climate change (Mariani and Fletcher 2016).

Establishing a rigorous deep historical benchmark for extreme fire occurrence over southeast Australia requires more detailed spatial and temporal reconstructions of past climatic conditions and fire occurrence, as well as increased knowledge of how charcoal is generated, deposited, and subsequently preserved during extreme fires.

4 Post-European changes in extreme bushfire and their drivers

4.1 Changes in the occurrence of very large fires and pyroCb

One unresolved component of the debate about the history of fire in Australia is the question of how fire frequency has changed since European colonisation; little, if any, consideration has been given to whether the occurrence of ExBs has increased. The Aboriginal-influenced fire regime is commonly depicted as frequent, low–intensity fires designed to increase the availability of resources (Bowman 1998). Land clearing associated with agriculture and property ownership, coupled with the European perception of fire as a destructive element, is thought to have resulted in a distinct change in fire regimes compared to the pre-European period (e.g. Burrows et al. 1995). Implicit in this thinking is that since European settlement of Australia, fires are likely less frequent and more intense. This notion is supported by studies into the post-1860 fire regime in the Australian Alps (Banks 1989), and of charcoal records. Indeed, Mooney et al. (2011) demonstrated that, at the continental scale (heavily biased toward southeast Australia), the accumulation of charcoal in the recent historic period is higher than at any other time during the last 70,000 years. Nevertheless, studies of tree rings and charcoal abundance do not provide any quantitative information on the power of the fires they represent.

Historical fire records provide some insight into temporal trends of very large fire events over the last century or so. While few detailed histories have been developed for Australia, the Victorian state government maintains records of major bushfires (not necessarily ExBs) that have occurred within Victoria between 1851 and 2013.[1] Typically, these fires burnt areas ranging from around 5000 ha to several hundred thousand hectares over a period of several days. The number of years between major bushfires in the state of Victoria for the period 1900–2015 is shown in Fig. 2a, including the major fires experienced in the Grampians (western Victoria) in 2014 (Fig. 1). Each point in Fig. 2a represents a year in which a major fire (or fires) occurred somewhere in Victoria, with the value of the ordinate representing the number of years since the previous major fire event. Overall, there is a decline in the interval between major fires and an approximate doubling of the frequency of major fires over the period (i.e., about a 6.9 year interval in 1900, compared to about a 3.5 year interval in 2015; Fig. 2a). There has also been consistently <5 years between major fire events in the last 15 years. Whilst subject to biases in the identification and reporting of fire events through time, Fig. 2a indicates a markedly decreasing interval between bushfire events over the course of the last century.

We can also consider trends in the occurrence of pyroCb events over southeastern Australia. Recently, McRae et al. (2015) provided a catalogue of confirmed or suspected Australian pyroCb events, identified from satellite data (Fromm et al. 2010). Figure 2b shows the accumulated occurrence of pyroCbs over southeastern Australia since 1978, when the satellite record began. The most notable feature of this record is the abrupt increase in occurrence over the last 10–15 years. It should be noted, however, that at the time of writing there is still no automated means of quantifying pyroCb occurrence in space and time, and the pre-1998 pyroCb occurrence data in Fig. 2b should be considered as tentative as further work is undertaken to produce robust counts going back to the beginning of the satellite record.

4.2 Changes in fire danger rating

Over the period 1970–2007 there has been a nonlinear increase in annual accumulated (daily) FFDI over Australia (Lucas et al. 2007). In southeastern Australia most meteorological stations

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[1] See www.depi.vic.gov.au/fire-and-emergencies/managing-risk-and-learning-about-managing-fire/bushfire-history. Accessed 4 February 2016.

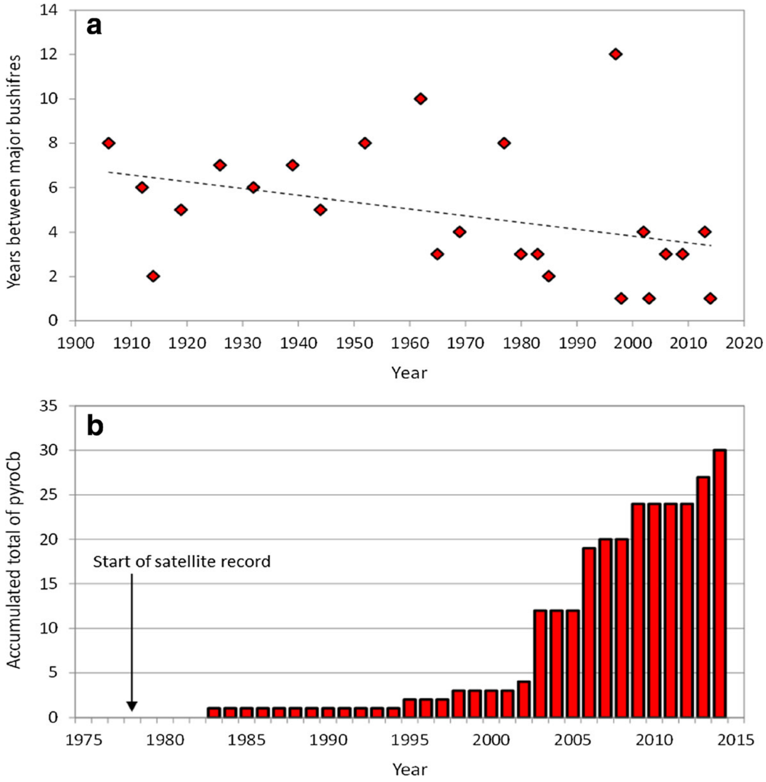

Fig. 2 **a** Years between major bushfire events in Victoria plotted against year. Red dots indicate years in which one or more major fires occurred. The black dashed line is a least-squares linear regression fit to the data indicating the trend; **b** Accumulated occurrence of pyroCb over southeastern Australia for the period 1975–2015

show a significant positive trend in FFDI (Clarke et al. 2013). The annual 90th percentile FFDI over the period 1973 to 2010 has increased significantly ($p < 0.1$) at a majority of the stations sampled across Australia (Clarke et al. 2013). The largest increases generally occurred in inland areas (although these areas are not forest) across the centre, south and east of Australia. Area burned has increased in some forest regions of southeastern Australia, but this has only been attributed to a generally observed warmer, drier trend in some cases (Bradstock et al. 2014). Therefore, the link between changes in surface fire weather and area burned is not particularly strong, and nothing can be inferred regarding ExBs in particular.

Jolly et al. (2015) emphasised the contribution of climatic droughts and widespread heatwaves to particularly bad fire seasons in southeast Australia, and noted the high inter-annual variability of fire weather extremes driven by the combined influence of ENSO and the IOD (also see Verdon et al. (2004)). Nevertheless, it remains unclear if the recent increases in fire danger across much of Australia have resulted from anthropogenic climate change (i.e., resulting from elevated CO_2 in the atmosphere) or can be attributable to natural climate variability (Cary et al. 2006; Clarke et al. 2013) and changes in forest management practices. Indeed, Williamson et al. (2016) note that the high variability of climate in Australia makes it difficult to discern long-term trends.

4.3 Changes in the c-Haines index

A number of studies have investigated the Haines and c-Haines indices over the recent past in various parts of the world (e.g. Mills and McCaw 2010; Lu et al. 2011; Tatli and Türkeş 2014). Here we examine trends in the c-Haines index calculated from the NSW/ACT Regional Climate Model (NARCliM) ensemble. NARCliM includes a 12-member regional climate projection ensemble (Evans et al. 2014) driven by a larger global ensemble to create a high resolution (10 km) ensemble of regional climate projections for southeastern Australia. Four global climate models were each downscaled using three regional climate models referred to as R1, R2 and R3.

Given our focus on ExB development, we restrict attention here to consideration of c-Haines values greater than or equal to 10, which approximately corresponds to the 95th percentile value over southeastern Australia (Mills and McCaw 2010). Figure 3a shows the total number of gridcell-days in the NARCliM reanalysis simulations satisfying this condition. There is a consistent increase in the occurrence of potential extreme fire conditions over recent decades, which is consistent with the trend in occurrence of noteworthy bushfires depicted in Fig. 2a.

Viewed collectively, all the indicators (fire size, pyroCb frequency, FFDI, cHaines) exhibit changes consistent with an increase in the occurrence of ExBs over southeastern Australia since European settlement.

5 Future changes to factors relating to extreme bushfire

5.1 Potential changes in fire danger rating

Assuming different possible future climate scenarios (e.g. RCP8.5 – high emissions, and RCP4.5 – low emissions; Riahi et al. (2011)), temperatures could rise by 2 to 4 °C or more across Australia by the end of the century, and the number of days above 35 °C could double or triple above historical baselines (CSIRO and Bureau of Meteorology 2015). Projections for precipitation declines of up to 150 mm per year in Australia's southwest by the end of the twenty-first century (Lim and Roderick 2009) are mirrored by projections for higher drought in Australia's south overall (CSIRO and Bureau of Meteorology 2015), although uncertainty about outcomes is high (Kiem et al. this issue). Projections indicate that average wind speed might not change by more than a few percent by the end of the century, particularly in summer, with similar changes expected for extreme wind speeds (CSIRO and Bureau of Meteorology 2015). Taken together, these projected changes in climate indicate a shift towards fire danger conditions that are more conducive to the development of ExBs.

Climate change projections associated with low and high emission scenarios across all or parts of Australia typically exhibit increases of around 10–30 % in annually accumulated FFDI (Beer and Williams 1995; Cary 2002; Pitman et al. 2007; King et al. 2011; CSIRO and Bureau of Meteorology 2015), although increases of 50 % by 2100 are reported for northern Tasmania (Fox-Hughes et al. 2014). Projections consistently indicate fewer days with lower fire danger and more projected days of higher fire danger (Williams et al. 2001; Hennessy et al. 2005). The number of days when FFDI is above 40, when there is a very high chance of bushfires resulting in house destruction in southern Australia (Bradstock and Gill 2001), could increase by 30 % to more than 200 % by 2100 in eastern Australia during months of highest fire danger (Clarke et al. 2011).

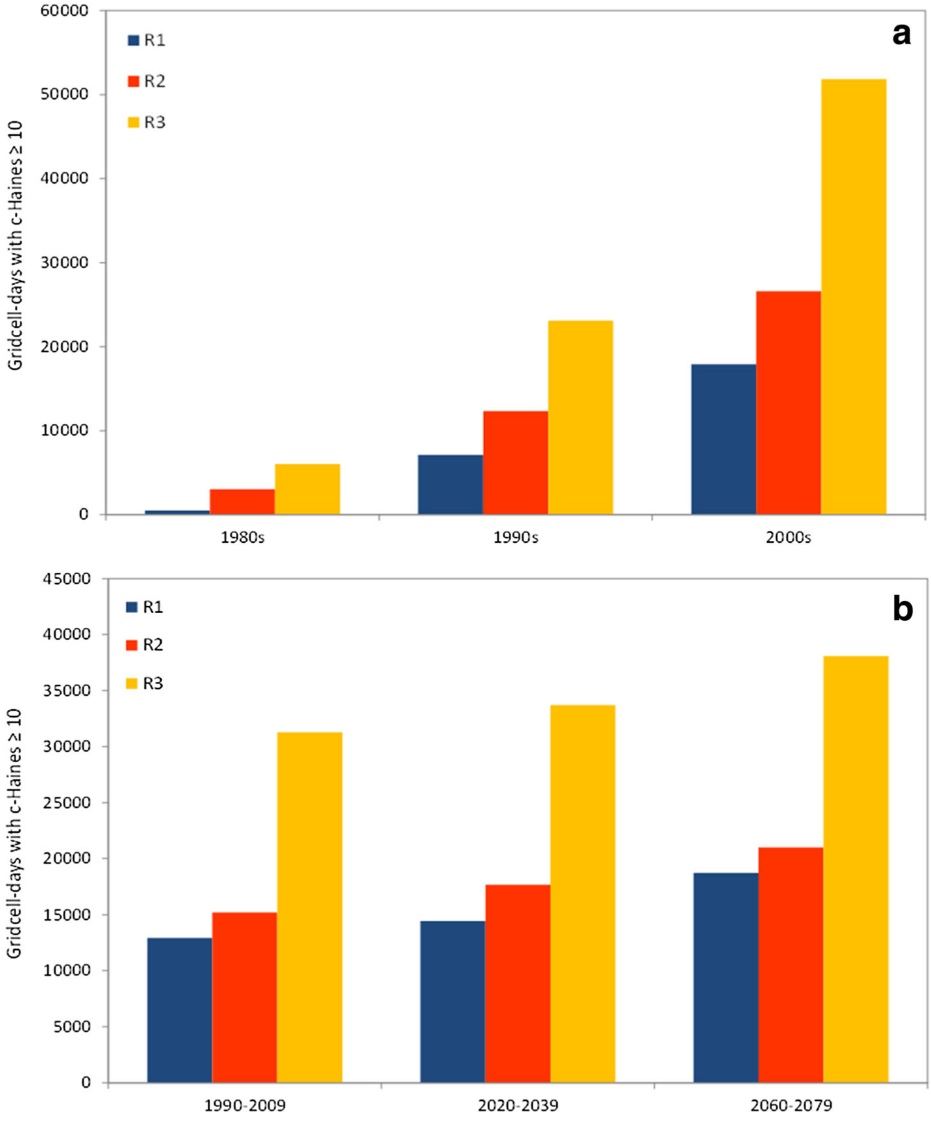

Fig. 3 **a** Number of gridcell-days per decade with the continuous Haines index ≥10, calculated from reanalysis driven NARCliM simulations for the satellite era (1980s onwards). R1, R2 and R3 correspond to each regional climate model; **b** Observed and projected number of gridcell-days with the continuous Haines index ≥10, calculated from the NARCliM regional projection ensemble for 20 year periods. R1, R2 and R3 correspond to the means for each regional climate model

However, fire behaviour modelling over southeastern Australia (Matthews et al. 2012) suggests that the higher rates of spread expected to result from direct effects of a warmer, drier climate may be ameliorated by lower fuel loads. Future fuel loads will reflect a balance between climate change induced biomass growth, fuel decay and fire consumption of fuel. Consequently, definitive projections for future fire dynamics will remain uncertain until these aspects are resolved.

5.2 Potential changes in the additional drivers of extreme bushfires

While many studies that have considered how fire danger might change under global warming scenarios during the current century, few have identified potential changes to the form and frequency of the weather systems that lead to particularly bad episodes of fire weather.

Studies of possible future changes in the Haines index in the USA indicated that the potential for extreme fire will increase in the future (Luo et al. 2013; Tang et al. 2015). Using the NARCliM ensemble to look at future changes in the c-Haines index in southeastern Australia provides a picture of increasing extreme fire risk consistent with that found in the USA. Figure 3b shows the average occurrence of extreme c-Haines index (i.e. ≥ 10) for each RCM, for each epoch simulated: the recent past (1990–2009); the near future (2020–2039); and the far future (2060–2079). Each RCM indicates a gradual increase into the far future. This suggests that the potential for fires to intensify into ExBs will increase due to climate change, with an average increase of approximately 30 % by 2070. Changes in dry lightning occurrence implied by the projected changes in the c-Haines index (Dowdy and Mills 2009) also need to be explored.

On larger scales the Hadley cell is expected to expand poleward under a warming climate (Seidel et al. 2008). Indeed, there is evidence that the Hadley circulation has expanded already in recent decades (Nguyen et al. 2013). In combination with changes in other climate drivers (e.g. SAM), this shift has driven rainfall decreases in southwest and southeastern Australia (Murphy and Timbal 2008; Hendon et al. 2014; O'Donnell et al. 2015; Lim et al. 2016). In particular, the number of frontal systems and low-pressure systems crossing southeastern Australia has decreased during autumn (e.g. Risbey et al. 2013), with the consequent reduction in rainfall affecting fuel moisture levels during the following fire season.

There is less certainty about historical and projected changes in the number of fronts crossing southern Australia during summer. There is, however, evidence that the number of very dangerous summertime fronts may increase during the current century (Hasson et al. 2009; Grose et al. 2014). "Very dangerous" fronts, in this context, are defined by the strength of the 850 hPa temperature gradient over a specific region, following Mills (2005). Other atmospheric structures may lead to dangerous fire weather, of course, including "negatively tilting" upper atmospheric troughs (Fox-Hughes 2015), which have been associated with abrupt increases in fire danger (Mills 2008). There is currently no evidence that the number of such features is likely to change through the course of the current century, but it is a topic that is worthy of investigation.

The severity of many fire weather events is increased by discrete mesoscale weather phenomena (e.g. Sharples et al. 2010; Sharples et al. 2012). These are challenging to study in future climate scenarios, unless associated with broader scale structures that are resolvable by coarser resolution climate models (e.g. Miller and Schlegel (2006)), or by use of fine-resolution regional climate models. Grose et al. (2014) and Fox-Hughes et al. (2014), using fine-scale regional climate model output, demonstrated an ongoing role of foehn-type winds and mesoscale low pressure systems in the occurrence of elevated fire danger in various parts of Tasmania.

6 Conclusions

Overall, the available historical information provides only weak suggestion of a possible increase in the occurrence of ExBs over southeast Australia. The main impediment to drawing stronger conclusions is the general lack of data that pertains specifically to ExBs. Given the relatively recent advances that have been made in understanding the key drivers for ExBs, the field is now ready for targeted studies to document these key drivers in both historical records and future projections. Such studies will assist in providing robust estimates of future ExB risk and allow consideration of appropriate adaptation strategies.

There is a paucity of long-term climatic and palaeo-environmental data that can be used to infer benchmark occurrence frequencies for *extreme* bushfires, which manifest as violent pyroconvective events. This being said, the available records tend to support the contention that fires have increased in frequency and changed in nature in southeastern Australia since European settlement. Such changes are consistent with observed broad-scale changes in fire weather conditions, although these broad-scale measures do not reflect the full set of factors contributing to the development of ExBs.

The influence of additional factors such as extended drought, heatwaves, discrete fire weather events, and atmospheric instability on changes in ExB occurrence have only received limited attention. In particular, questions remain about the suitability of the existing methodology to account for the effects of extended drought and heatwaves on the larger fuel elements that contribute to very large fires. It is likely that a more comprehensive consideration of bushfire fuel availability is necessary to fully understand how changes in drought and heatwaves will impact the occurrence of ExBs (see also Perkins-Kirkpatrick et al. and Kiem et al. in this issue for further information).

Analysis of c-Haines levels over southeast Australia indicated an increasing trend in mid-level atmospheric instability over the last few decades, consistent with observed trends in major bushfire occurrence. Climate projections indicated further increases into the future, with the potential for ExBs driven by atmospheric instability rising accordingly. However, to properly understand the future potential for ExBs these findings need to be considered in combination with the changes expected for other factors such as fuel load and type (Bowman et al. 2014), which is a significant intellectual challenge.

Understanding the likely changes in the occurrence of meso-scale fire weather events under projected future climate requires establishing relationships between fire weather and broader-scale synoptic patterns that can be adequately resolved in global climate models. The influence of larger-scale drivers such as ENSO and the IOD will further complicate the process of gaining a rigorous understanding of how discrete fire weather events will affect the occurrence of ExBs.

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